Renewable and Sustainable Energy Reviews 33 (2014) 602–612

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Modeling of solar PV module and maximum power point tracking using ANFIS

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ARTICLE INFO

Article history:
Received 23 October 2013
Received in revised form
11 February 2014
Accepted 18 February 2014
Available online 12 March 2014

Keywords:
Photovoltaic (PV) module
Maximum power point tracking (MPPT)
Adaptive neuro-fuzzy inference system (ANFIS)
DC–DC boost converter
PI controller

ABSTRACT

Solar energy, at the present time is considered as an important source in electricity generation. Electricity from the solar energy can be generated using solar photovoltaic (PV) modules. The maximization of solar power extracted from a PV module is of special concern as its efficiency is very low. The output power of a PV module is highly dependent on the geographical location and weather conditions such as solar irradiation, shading and temperature. To obtain maximum power from PV module, photovoltaic power system usually requires maximum power point tracking (MPPT) controller. In this paper, an adaptive neuro-fuzzy inference system (ANFIS) based maximum power point tracker for PV module has been presented. To extract maximum power, a DC–DC boost converter is connected between the PV module and the load. The duty cycle of DC–DC boost converter is modified with the help of the ANFIS reference model, so that maximum power is transferred to load. Due to the complexity of the tracker mechanism and non-linear nature of photovoltaic system, the artificial intelligence based technique, especially the ANFIS method, is used in this paper. In order to observe the maximum available power of PV module, the ANFIS reference model directly takes in operating temperature and irradiance level as input. The response of proposed ANFIS based control system shows accuracy and fast response. The simulation result reveals that the maximum power point is tracked satisfactorily for varying irradiance and temperature of PV module. Simulation results are provided to validate the concept.

Contents

1. Introduction

The fossil fuel reserves are depleting at a rapid rate and their use for electric power generation is degrading our environment at even

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http://dx.doi.org/10.1016/j.rser.2014.02.014
1364-0321

faster rate. It is the need of the hour to develop commercially feasible and environment friendly alternative sources of electric power generation. Sunlight is an excellent source of energy which can be utilized for electric power generation. Solar energy is renewable which is the best option for electricity generation because it is never-ending, non-polluting and free to harness. Moreover the solar energy is available everywhere in huge amount. Various benefits of solar power have been identified for different sectors and are tabulated in [1]. With the advancements in solar technology [58,59], the uses of solar power have diversified, expanded and become commercialized.

Solar power might replace fossil fuel dependent energy sources very soon; however solar power cost per kilowatt-hour has to be competitive with fossil fuel energy sources [4,5]. At present, solar modules are not very efficient with their ability to convert sunlight to electrical power [3,56]. The efficiency can drop further due to other factors such as solar module temperature, available sunshine and load conditions. Solar module characteristics are dynamic in nature and their power generation capabilities keep on changing with the geographical location and weather conditions [2]. The temperature dependence of solar electrical efficiency of PV modules and analysis of variation of the junction temperature with the radiation intensity and ambient temperature is briefly discussed in [49,53]. A simple model is proposed in [55] to predict the dependence of PV module performance upon solar-irradiance intensity and temperature. In the literature, many methods have been proposed to extract maximum power from PV module [6–21]. The proposed methods can be broadly classified as the perturb & observation (P&O) method, the incremental conductance (INC) method and artificial intelligence (AI) based methods. Although the P&O method [9,10,13] is commonly used in the MPPT applications due to its simplicity and easy implementation, it has number of problems. Its accuracy in steady-state sunshine condition is low because the perturbation process would make the operating point of the PV module oscillate around the MPP, which consequently waste the energy. By minimizing the perturbation step size, oscillation can be reduced, but a smaller perturbation size slows down the speed of MPPT. Further, the P&O method probably fails to track the maximum power point due to the sudden changes in sunshine. The INC method [6,7,19,54] has been proposed to improve the tracking accuracy and dynamic performance under rapidly varying environmental conditions. The advantages of the INC method over the P&O method have been analyzed in [60]. The INC method is based on the fact that the slope of the PV module power curve is zero at the MPP, positive on the left side and negative on the right side of the MPP. It uses the derivative algorithm to find the MPP. This method requires more computation in the controller because the differentiation process involves a relatively complex decision making process. Therefore the INC method needs more complex calculation capacity and memory [16,20,22,46], which may increase the cost of system. Moreover, the results of the INC method are unsatisfactory at low level of irradiance as the differentiation process becomes difficult.

The performance of different maximum power point tracking techniques is compared in [11,17,46]. As per [48], most of the presented methods in literature suffer from the drawback of poor stability and can produce oscillations in power output due to the highly non-linear characteristics of the PV module. In addition to that, it is impossible for the conventional methods to quickly acquire the maximum power points for the power generated by PV modules and

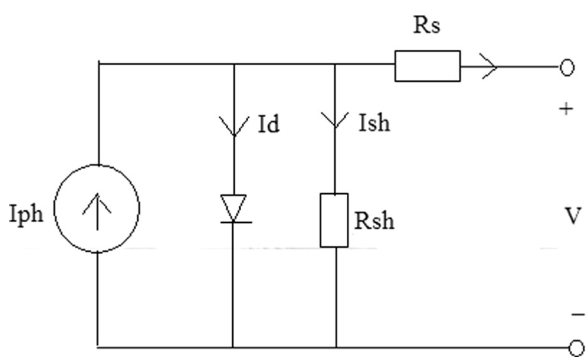


Fig. 1. Equivalent circuit of solar cell.

Table 1
Key specification of MXS 60 PV module.

Parameter	Variable	Value
Maximum power	Pm	60 W
Maximum voltage	Vm	17.1 V
Current at max power	Im	3.5 A
Open circuit voltage	Voc	21.06 V
Short circuit current	Isc	3.74 A
Total no. of cells in series	Ns	36
Total no. of cells in parallel	Np	1

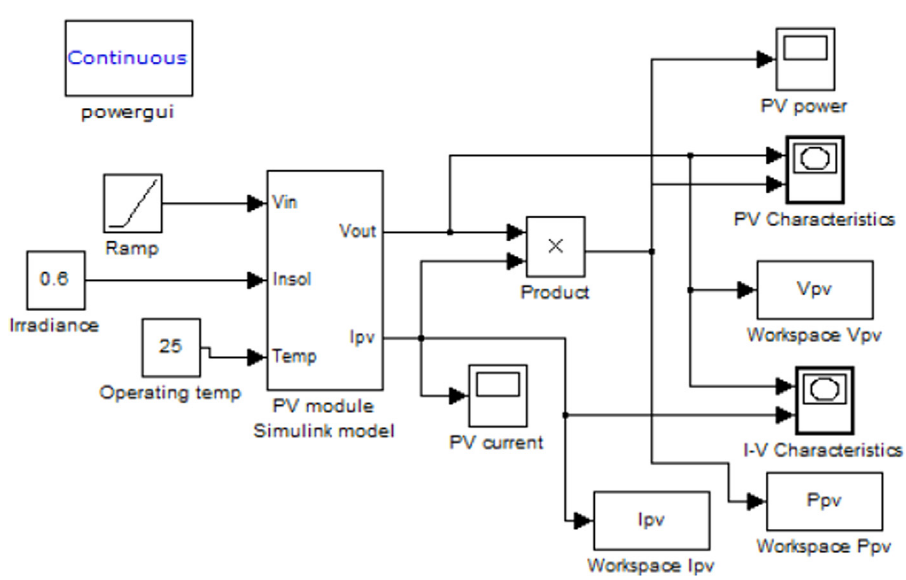


Fig. 2. Matlab/Simulink model of PV module.

arrays [52]. AI based techniques offer highly accurate and flexible nature of control in non-linear systems. Artificial intelligence methods have been proposed in literature [22–36,45] to improve the dynamic performance of extracting maximum power from PV module. Concentrating on non-linear characteristics of the PV modules, the AI methods provide a fast, and yet, computationally demanding solution for this problem. The AI methods are mainly based on fuzzy logic controller and artificial neural networks. The detection and controlling of maximum power point using different configurations of fuzzy logic MPPT controller is presented in [23,27,31,36,47]. An adaptive fuzzy logic controller for grid-connected photovoltaic system is presented in [57]. Fuzzy logic controllers have the advantage of being robust and relatively simple to design because they do not require knowledge of the exact model [11]. Fuzzy logic controllers use the expert knowledge for the establishment of rules of inference. But the effectiveness of fuzzy logic control for MPPT depends a lot on the knowledge of the user or control engineer in choosing the right error computation and coming up with the rule base table [6,11]. Another disadvantage of fuzzy logic control is complex algorithms which results in the high cost of implementation [10]. On the other hand, the artificial neural network models are based on the electronic neural structure of the brain which can be used to find the position of the maximum power point with reduced number of iterations and oscillations around maximum power point. The MPPT controllers for PV systems using neural networks have been presented in [29,35,50]. A neural network control operates like a black box model, requiring no detailed information about the PV system. After learning relation between maximum power point voltage and open circuit voltage or irradiance level and temperature, the neural network control can track the maximum power point online. An adaptive neuro-fuzzy inference system (ANFIS) is a hybrid between neural networks and fuzzy logic which combines the advantages of the two, making it the most powerful artificial intelligence technique. Thus, in this paper, using Matlab/Simulink, an ANFIS based model is presented which takes in operating temperature and irradiance level as input to extract maximum power from PV module. The MPPT methodology using neuro-fuzzy network is presented in [22,28,30]. ANFIS is used in [25,26, 32–34,45] to track the maximum power point. The fuzzy rules used in the presented MPPT method are developed by ANFIS which are more accurate than the fuzzy logic control method because rules are derived according to the input and output mapping of actual training data. Moreover ANFIS constructs an input output mapping using a hybrid algorithm of the least-squares and the backpropagation gradient descent method. In the present work, PI controller is used to generate the required control signals in contrast to [25], where fuzzy logic controller is used for this purpose. Use of PI controller reduces the

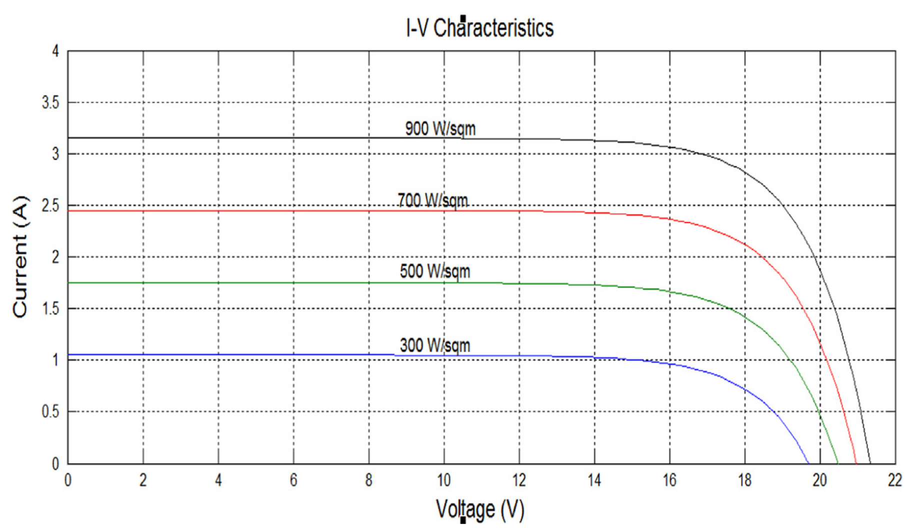


Fig. 3. *I–V* characteristics at constant temprature and variable irradiance level.

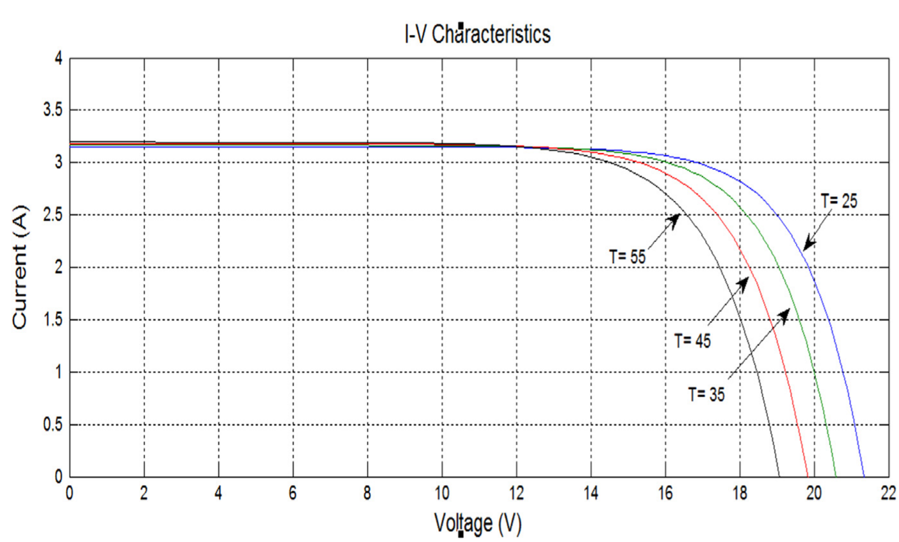


Fig. 4. *I–V* characteristics at variable temprature and constant irriadance level.

level of complexity of control algorithm. Unlike neural networks, ANFIS is not a black box model and is well suited to mathematical analysis. Considering the non-linear characteristics of solar PV module, the output waveforms depict that the response of ANFIS based MPPT method is more accurate, fast and gain is higher as compared to the conventional methods of MPPT.

1.1. Organization of the paper

Matlab/Simulink modeling and characteristics of PV module are described in Section 2. Need of maximum power point tracking for a PV module is explained in Section 3. In Section 4, MPPT using ANFIS is presented. Training of ANFIS model is also described in Section 4. The results and discussion of this research are given in Section 5, followed by conclusions and future work in Section 6.

2. Modeling and characteristics of PV module

Equivalent circuit model of PV module is an important tool to understand the operation of device and the dynamic interactions between parameters. In this paper, PV module is described using various mathematical equations and user friendly Matlab/Simulink environment is used to simulate the PV module.

2.1. Equivalent circuit of PV module

The ideal equivalent circuit of solar cell is a current source in parallel with a single-diode. The configuration of an ideal solar cell with single-diode is shown in Fig. 1 [37–39,43]. For the purpose of the electrical characteristics of a solar cell, it can be described by an electric circuit with only four components. The ideal solar cell consists of a single diode connected in parallel with a light generated current source, Iph. Rs and Rsh represent the series and shunt resistance of solar cell. A method to estimate the equivalent circuit parameters of a PV module is presented by Ikegami et al. [51]. Usually the value of Rsh is very large and that of Rs is very small, hence they may be neglected to simplify the analysis [39–41,44]. The output power of single solar cell is very less and it cannot be used for almost any application. So in order to increase the capability of the overall PV system, the solar cells are

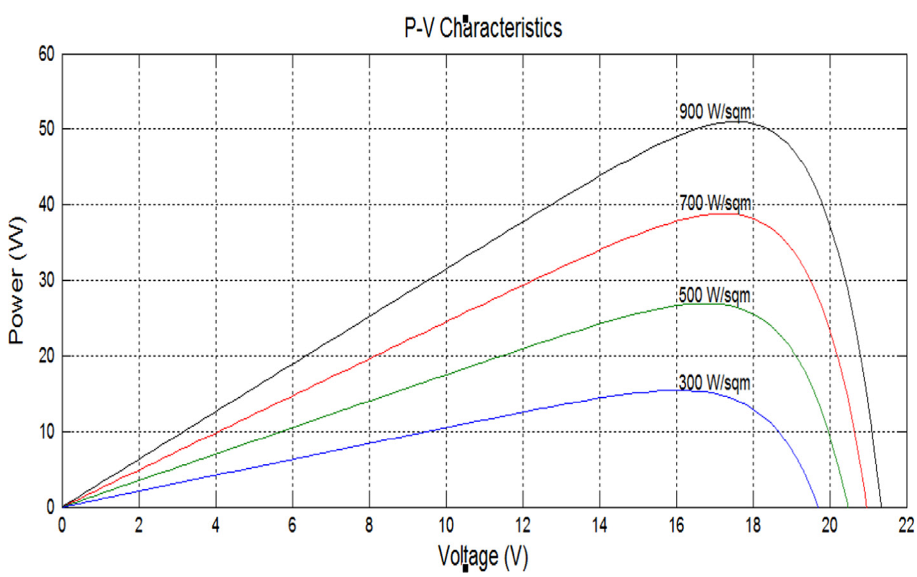


Fig. 5. *P–V* characteristics at constant temprature and variable irradiance level.

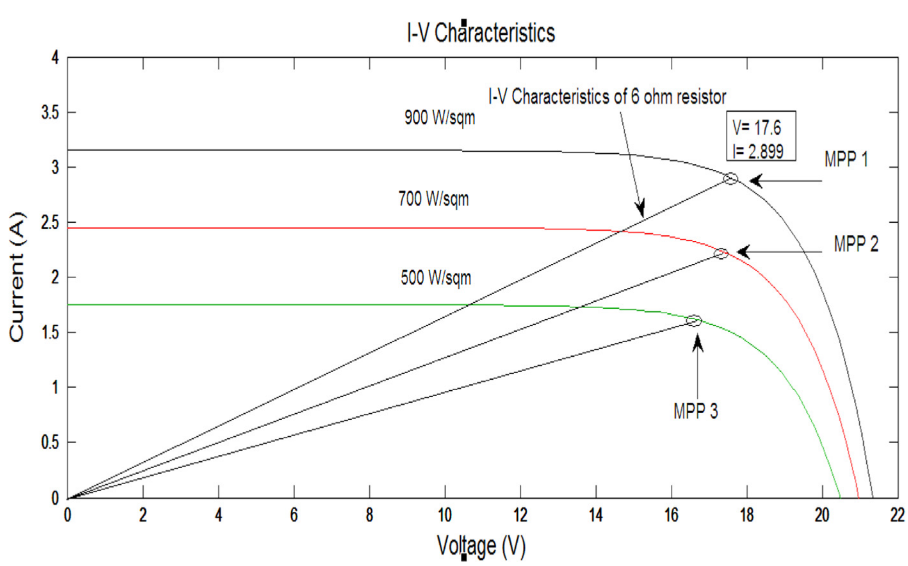


Fig. 6. Changing location of MPP with irradiance level.

connected in series and parallel configurations to form solar modules and arrays [42].

2.2. Equations of PV module

From the theory of semiconductors and photovoltaic, following are the basic equations that mathematically describe the current–voltage relationship of the PV module.

(i) The output current of PV module is given as

$$I = \text{Np Iph} - \text{Np Is}\left[\exp\frac{q(V+\text{IRs})}{\text{Ns } kTA} - 1\right] \quad (1)$$

where, Iph is the light-generated current or photocurrent; Is is the module saturation current; q is the electron charge (1.6×10^{-19}C); k is the Boltzmann constant (1.38×10^{-23} J/K); T is the cell working temperature; A is the ideal factor of cell dependent on PV technology; Rsh is the shunt resistance; Rs is the series resistance; Ns is the number of cells connected in series and Np is the number of cells connected in parallel.

(ii) The module photocurrent depends linearly on the solar irradiation and is also influenced by the temperature according to the following equation:

$$\text{Iph} = [\text{Isc} + \text{Ki}(T - \text{Tr})]\lambda \quad (2)$$

where, Isc is the cell short-circuit current at a 25 °C and 1 kW/m^2; Ki is the cell short-circuit current temperature coefficient; Tr is the cell reference temperature and λ is the solar irradiance level in kW/m^2.

(iii) The module saturation current varies with the cell temperature, which is given by

$$\text{Is} = \text{Irs}\left(\frac{T}{\text{Tr}}\right)^3 \exp\left[q\text{Eg}\,\frac{1/\text{Tr} - 1/T}{kA}\right] \quad (3)$$

where, Irs is the reverse saturation current at a reference temperature and solar radiation; Eg is the band-gap energy of the semiconductor used in the cell.

(iv) The reverse saturation current of module, at reference temperature is given by

$$\text{Irs} = \frac{\text{Isc}}{\exp\left[\frac{q\text{Voc}}{\text{Ns } kAT}\right] - 1} \quad (4)$$

where, Voc is the PV open-circuit voltage at the reference temperature.

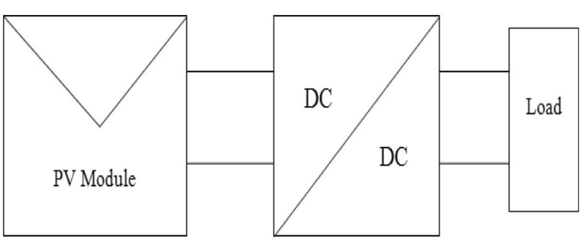


Fig. 7. Block diagram of a typical MPPT system.

2.3. Matlab/Simulink model of PV module

Using basic mathematical equations of PV module, a Matlab/Simulink model of PV module is developed as shown in Fig. 2.

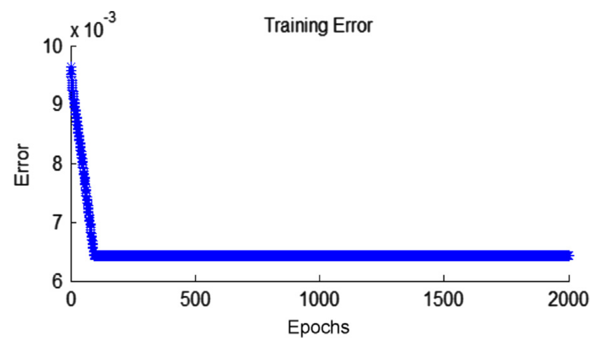


Fig. 9. Training error vs. epochs for ANFIS.

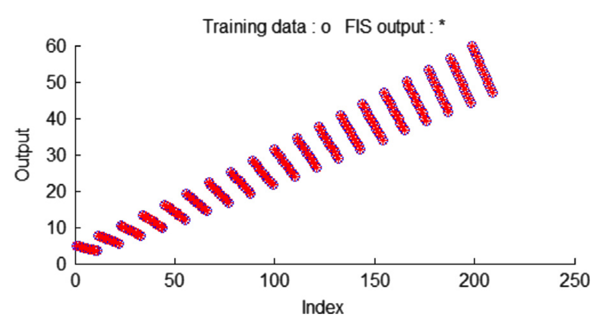


Fig. 10. Training data and ANFIS output.

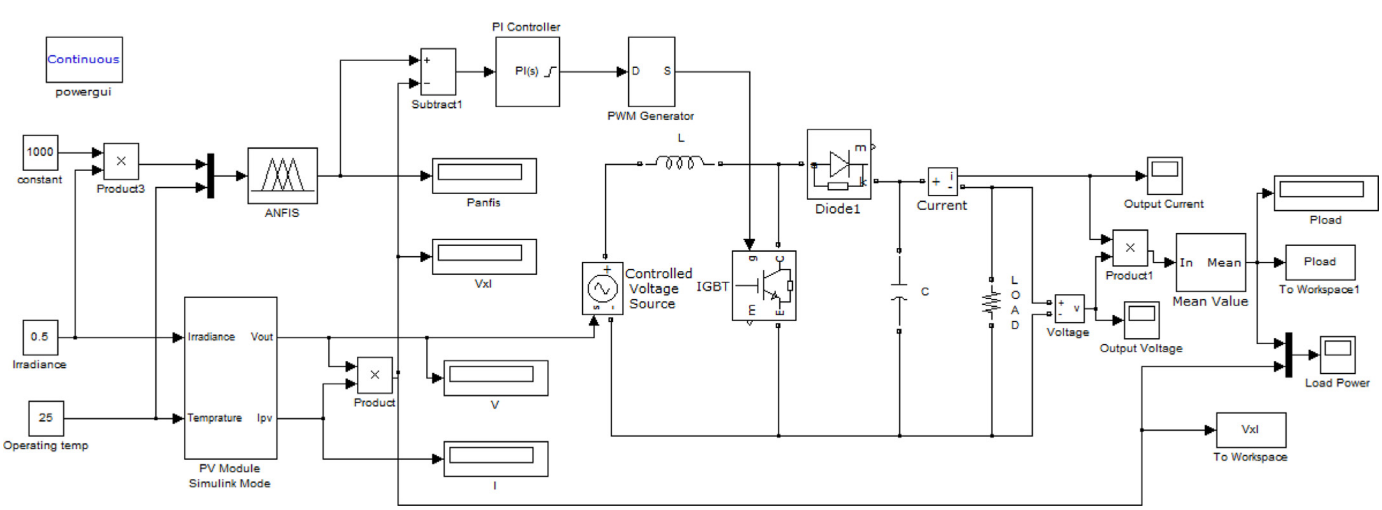


Fig. 8. Matlab/Simulink model of ANFIS based MPPT controller.

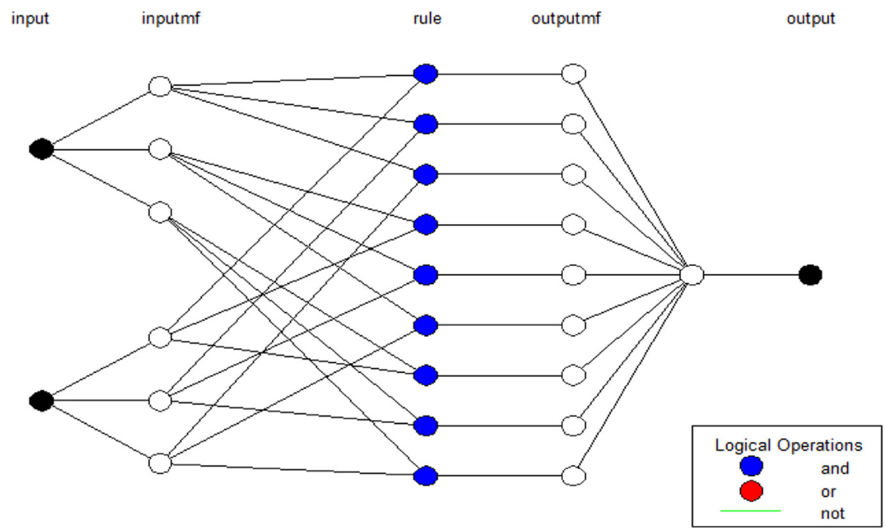


Fig. 11. ANFIS structure.

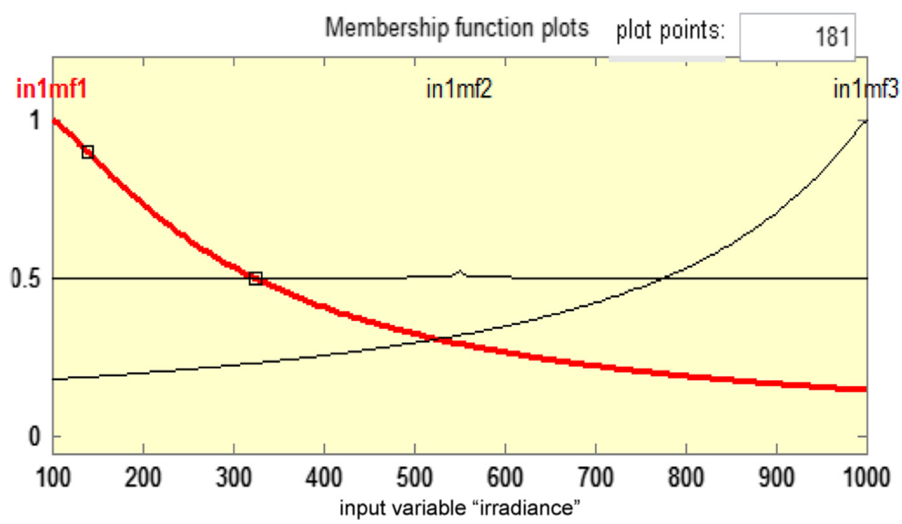


Fig. 12. Membership functions of ANFIS input (irradiance level) after learning.

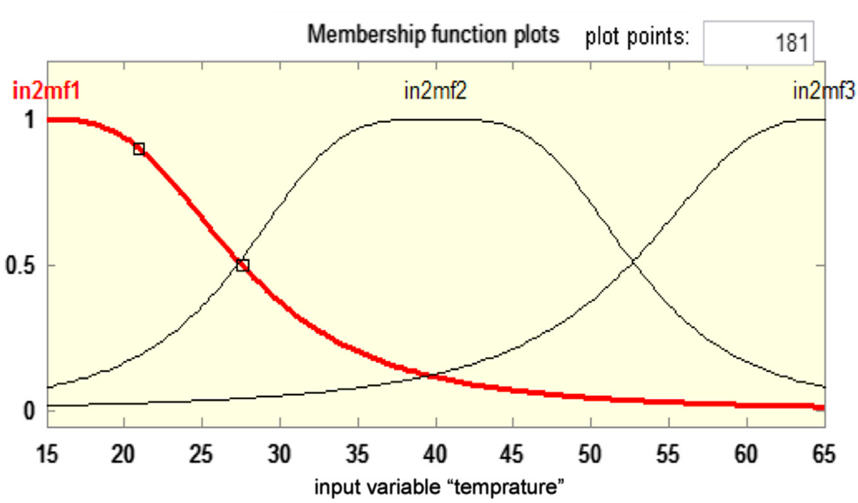


Fig. 13. Membership functions of ANFIS input (temperature) after learning.

MXS 60 PV module is taken as the reference module for simulation and the data sheet details are given in Table 1 [39].

2.4. Characteristics of PV module

The electrical characteristics of PV module are represented by the current versus voltage (*I–V*) and power versus voltage (*P–V*) curves. Both *I–V* and *P–V* output characteristics of PV module at various irradiance level and operating temperatures are derived from the simulated model and the results are shown in Figs. 3–5.

From Figs. 3 and 4, it is observed that with the increase in irradiance level, both short circuit current and open circuit voltage, increases. With the increase in operating temprature, open circuit voltage decreases whereas short circuit current increases marginally.

Fig. 5 indicates that with the increase in irradiance level, maximum output power from PV module, also increases.

3. Need of MPPT

The typical *P–V* and *I–V* curves of PV module indicate that the maximum power is available only at one specific operating condition, called maximum power point (MPP). Location of this MPP keeps on changing with irradiance level and operating temperature as shown in Fig. 6.

In Fig. 6, maximum available power at irradiance level of 900 W/m^2 is 51 W (approx.) which occurs at 17.6 V and 2.889 A (MPP1). In order to extract maximum power from the PV module, it is required to connect a load resistance given by

$$R_{load} = \frac{17.6\ \text{V}}{2.889\ \text{A}} = 6\ \Omega$$

But as the sun conditions change, the "maximum power resistance" must also change for getting maximum available power from PV module. But this is not practically feasible to change load resistance for every other irradiance level. To extract maximum power, a boost converter is connected between the module and the load resistor, and duty cycle of converter is used to modify the equivalent load resistance as seen by the source, so that maximum power is transferred between PV module and load resistance. A typical scheme of extracting maximum power from PV module using boost converter is shown in Fig. 7.

Thus extracting maximum available power from a PV module, called maximum point tracking (MPPT) is done by maximum power point tracking controllers. The MPPT controller tracks the output voltage and current from the solar cell and determines the operating point that will deliver the maximum power. A properly designed MPPT controller should be able to track the continuously changing operating point for maximum power in order to increase the efficiency of PV module.

4. MPPT using ANFIS

The proposed Matlab/Simulink model of ANFIS based maximum power point tracking controller is depicted in Fig. 8. Irradiance level and operating temperature of PV module are taken as the input training data set for the ANFIS. The ANFIS reference model gives out the crisp value of maximum available power from the PV module at a

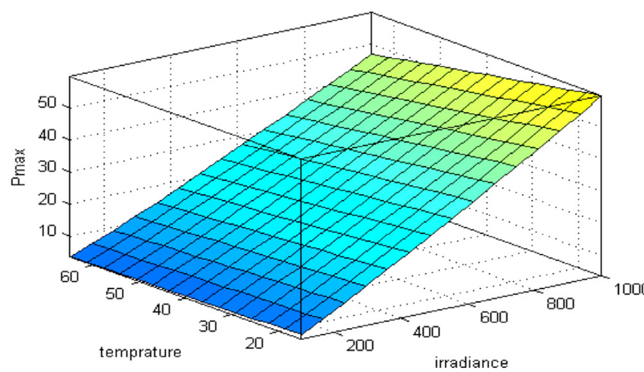


Fig. 15. Surface between two inputs (temperature and irradiance) and one output (maximum power).

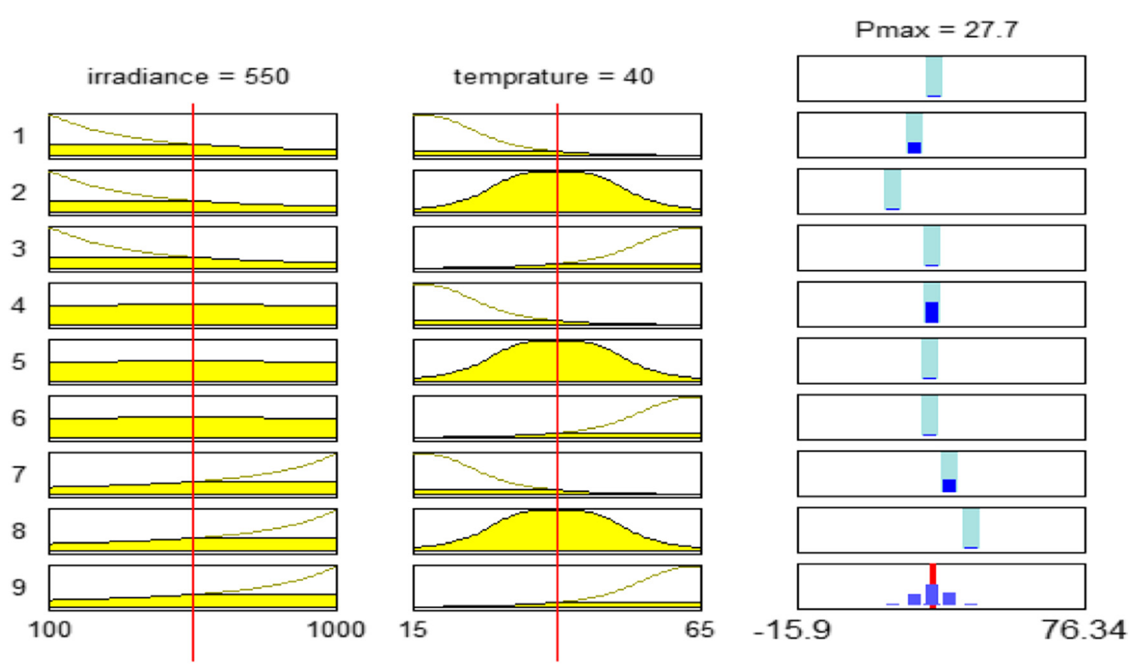


Fig. 14. Output from fuzzy rules for specific value of temperature and irradiance.

specific temperature and irradiance level. At the same temperature and irradiance level, the actual output power from the PV module, is calculated using the multiplication algorithm of sensed operating voltage and current. Two powers are compared and the error is given to a proportional integral (PI) controller, to generate control signals. The control signal generated by the PI controller is given to the PWM generator. The PWM signal is generated using high frequency of carrier signal as compared to the control or modulating signal. The frequency of carrier signal used is 50 kHz. The generated PWM signals control the duty cycle of DC–DC converter, in order to adjust the operating point of the PV module.

4.1. Tuning of ANFIS

Using the Matlab/Simulink model of PV module, the operating temperature is varied from 15 °C to 65 °C in a step of 5 °C and the solar irradiance level is varied from 100 W/m^2 to 1000 W/m^2 in a step of 50 W/m^2, to get the training data sets for ANFIS. Maximum available power for each pair of training data is recorded. In total 209 training data sets and 2000 epochs are used to train the ANFIS. By using given input/output data set, the ANFIS constructs a fuzzy inference system (FIS) whose membership function parameters are tuned using the hybrid optimization method of training the FIS. The hybrid optimization method is a combination of the least-squares type of method and the backpropagation algorithm. The training error is reduced to approximately 6% and the training waveform is shown in Fig. 9.

Fig. 10 shows the training data and ANFIS output. It depicts that the ANFIS output closely matches to the actual output of module even at 6% of training error.

The structure of ANFIS, generated by the Matlab code is a five layer network as shown in Fig. 11. It has two inputs (irradiance level and operating temperature), one output and three membership functions for each input.

The membership functions for each input, which are learned by ANFIS method, are shown in Figs. 12 and 13. Nine fuzzy rules are derived from six input membership functions. These rules are derived according to the input and output mapping, so as to produce maximum output power for each value of input temperature and irradiance level. Fig. 14 shows output of fuzzy rule for a specific value of operating temperature and irradiance level.

The ANFIS generated surface is shown in Fig. 15. It is 3-dimensional plot between temperature, irradiance and maximum power. The ANFIS surface indicates that the maximum available power from PV module increases with increase in irradiance level and moderate temperature. This clearly verifies

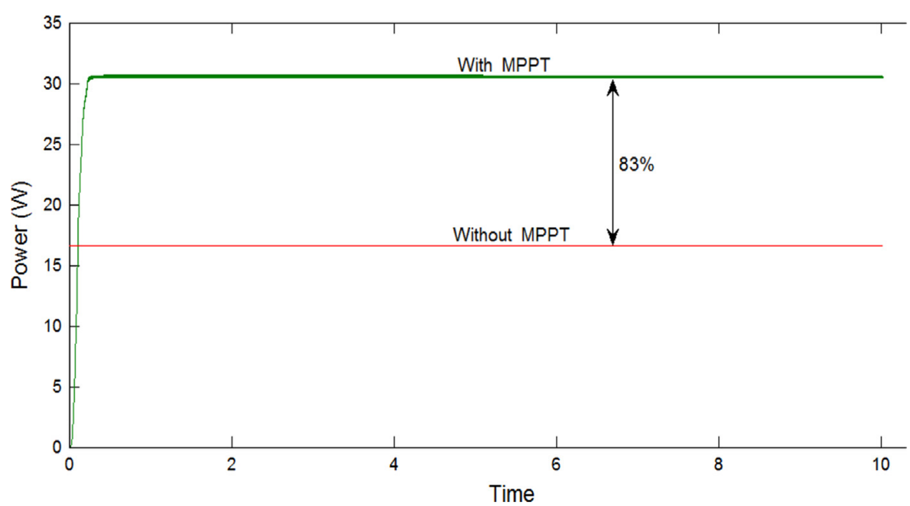


Fig. 16. Power vs. time with and without MPPT for 500 W/m^2 irradiance.

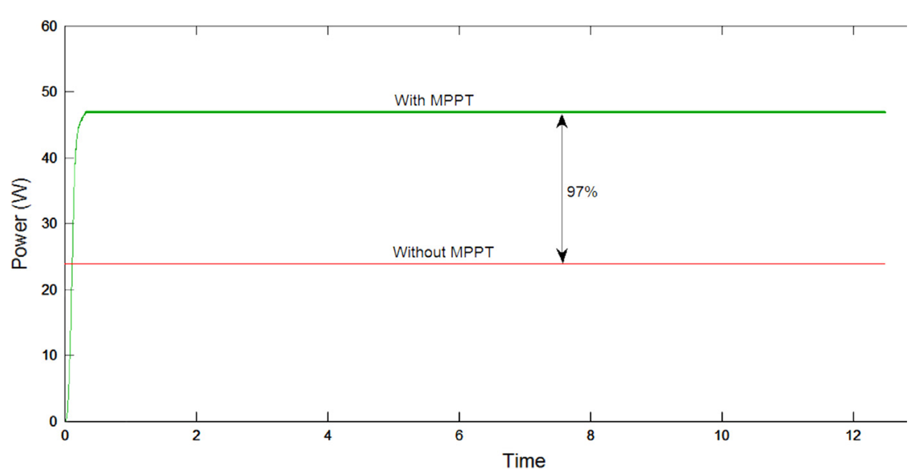


Fig. 17. Power vs. time with and without MPPT at 600 W/m^2 irradiance.

the *P–V* and *I–V* curves obtained from the Matlab/Simulink model of PV module in Section 2.

5. Results and discussion

The Matlab/Simulink model of PV module, developed in Section 2, is used to test the proposed ANFIS based MPPT control scheme. One DC–DC boost converter is connected between PV module and a resistive load for impedance matching and transfer of maximum power between PV module and load. ANFIS based control scheme is used here to vary the duty cycle of boost converter, so that maximum available power can be transferred to load. For comparing the results of ANFIS based control scheme, same PV module is connected directly to the load without any controller. Figs. 16 and 17 depicts the output power of PV module with and without MPPT scheme at irradiance level of 500 W/m^2 and 600 W/m^2 respectively. It is clearly seen that the output power of PV module is increased by 83% at an irradiance level of 500 W/m^2 and by 97% at irradiance level of 600 W/m^2 with ANFIS based control scheme.

The resulting waveforms of voltage and current at irradiance level of 600 W/m^2 is given in Figs. 18 and 19 respectively. It is observed from the waveforms that output voltage and current quickly reach to their maximum value.

The results obtained from ANFIS based MPPT method shows several benefits over other conventional methods of MPPT. ANFIS based MPPT method consumes no power in perturbation for maximum power point unlike the conventional P&O method [13]. The main advantage of the presented MPPT method is that it can easily pick the rapidly changing environmental conditions (like temperature and irradiance level) without producing intrinsic steady state oscillations near the maximum power point.

6. Conclusions

In this paper, an adaptive neuro-fuzzy inference system based maximum power point tracking controller has been proposed for a solar PV module. The operation of ANFIS based MPPT controller is investigated under varying weather conditions. After a proper training of presented ANFIS model, the ANFIS based MPPT controller has successfully tracked the maximum available power at different weather conditions. In the resulting waveforms of output power, voltage and current, the maximum value is reached in quick time with high gain, which depicts that the response of proposed ANFIS based

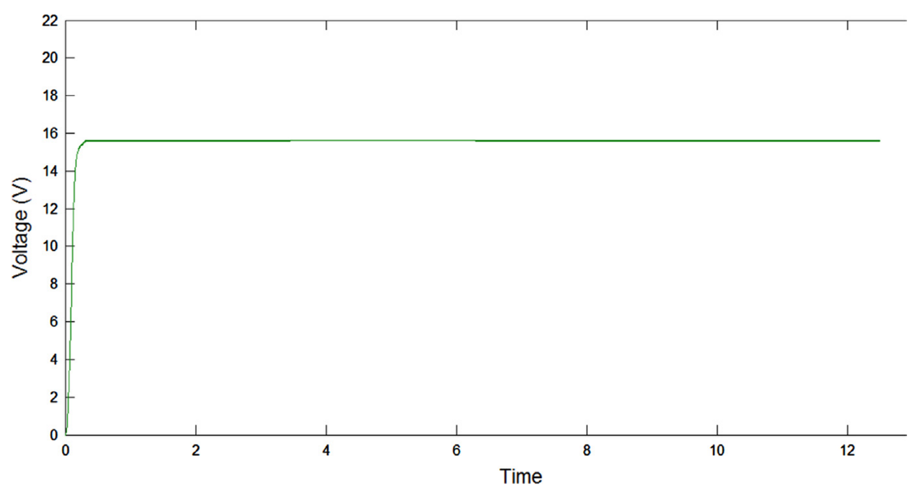


Fig. 18. Output voltage vs. time at 600 W/m^2 irradiance.

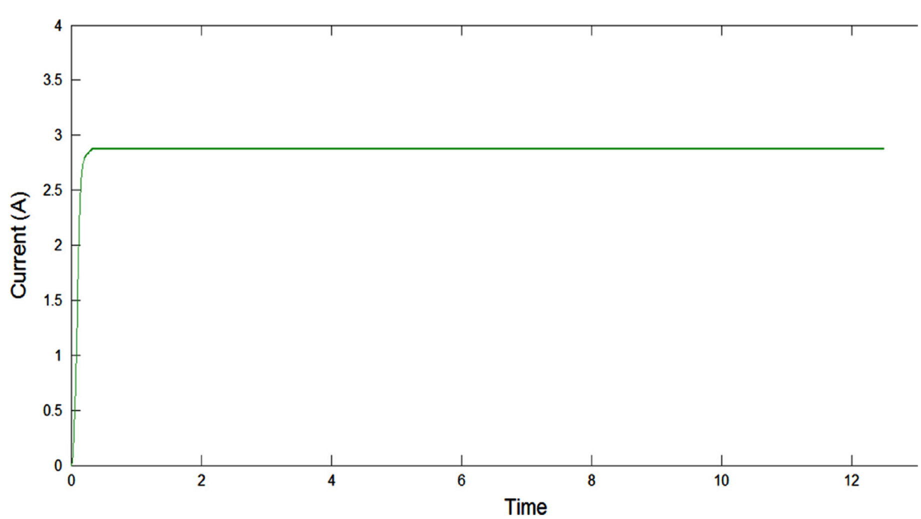


Fig. 19. Output current vs. time at 600 W/m^2 irradiance.

MPPT controller is extremely fast with good dynamics and the gain in the output power is significantly higher at all solar irradiance conditions. So, the ANFIS based control is an effective tool to track and extract maximum power from PV module.

6.1. Future work

Hardware implementation of the proposed ANFIS based MPPT controller by interfacing Matlab with PV module and boost converter using parallel ports. Solar photovoltaic system for grid connectivity can be developed using inverter and ANFIS based MPPT controller. An efficient MPPT controller of low cost and small size can be realized using a microcontroller and ANFIS based control scheme.

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